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Hot deformation behavior, dynamic recrystallization, and physically-based constitutive modeling of plain carbon steels

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ABSTRACT

The high-temperature deformation behaviors of low and medium carbon steels with respectively 0.06 and 0.5 wt% C were investigated under strain rate and temperature ranges of 10^{-4}–10^{-1} s^{-1} and of 900–1100 °C. Three types of dynamic recrystallization (DRX) flow behaviors were identified, namely single peak, multiple transient steady state (MTSS), and cyclic behaviors. The normalized critical stress (and strain) for the low and medium carbon steels were about 0.846 (0.531) and 0.879 (0.537), respectively. For both steels, the apparent deformation activation energy and the power of the hyperbolic sine law were found to be near the lattice self-diffusion activation energy of austenite (270 kJ/mol) and 4.5, respectively. As a result, it was concluded that the flow stress of plain carbon steels in hot deformation is mainly controlled by dislocation climb during their intragranular motion, and based on physically-based constitutive analysis, it was found that carbon has a slight effect on the hot flow stress of plain carbon steels. The significance of the approach used in this work was shown to be its reliance on the theoretical analysis based on the deformation mechanisms, which makes the comparison more reliable.

1. Introduction

Deformation temperature, strain rate, strain and interpass times must be carefully monitored to achieve required shape, microstructure, and mechanical properties. During hot working, dynamic recovery (DRV) and dynamic recrystallization (DRX) are the restoration phenomena that significantly affect the flow behavior. Due to the low stacking fault energy of austenite, the kinetics of DRV is slow and hence the DRX process normally occurs during hot forming of steels, which initiates at a critical strain (ε_c). Generally, three types of DRX flow curves have been proposed: single peak [1], multiple transient steady state (MTSS) [2,3], and cyclic [4,5] behaviors, which are dependent on the level of flow stress (deformation temperature and strain rate) and initial grain size [6]. The understanding of the hot deformation behavior together with the constitutive relations describing material flow is a prerequisite for large-scale production in the industry. The constitutive modeling of flow stress is thus important in forming processes because any feasible mathematical simulation needs accurate flow description [7–9].

Carbon is the most important alloying element in steels, which controls their microstructure and properties. Therefore, characterizing the effect of carbon on hot working behavior of steels is of special importance. For instance, its effects on the initiation of DRX, type of DRX flow curves, and hot strength of steels is essential in production of steel parts. To investigate the effect of carbon, it is logical to consider plain carbon steels with different carbon contents. In the current work, an attempt has been made to fundamentally enlighten these points based on the physically-based constitutive modeling, which result to a more reliable comparison. Indeed, on the experimental front, this problem has been studied before, as will be discussed in the results and discussion section, but the obtained results seem to be contradictory as some researchers have concluded that increasing the amount of carbon promotes hardening while some others have observed a reverse trend [10–14].

2. Experimental details

The chemical composition of the studied low carbon (0.06 wt%) and medium carbon (0.5 wt%) steels is shown in Table 1. Uniaxial hot compression tests were performed on cylindrical samples with the height of 11.4 mm and diameter of 7.6 mm. The strain rate and temperature for this work were in the range of 10^{-4}–10^{-1} s^{-1} and

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Table 1
Chemical compositions (wt%) of the studied plain carbon steels.

Element	C	Mn	Si	P	S	Cu
Low carbon steel	0.06	0.42	0.12	0.002	0.005	0.13
Medium carbon steel	0.50	0.68	0.2	0.002	0.038	0.28

900–1100 °C, respectively. Samples were soaked at 1100 °C for 15 min before the compression test and argon flow was employed to inhibit decarburization of the steels and oxidation of the machine tools. The initial grain size measured after quenching the as-received materials from the austenitization condition was ~78 μm and ~53 μm for the medium carbon and low carbon steels, respectively. More information about the experiments and preliminary hot deformation behaviors can be found elsewhere [15]. Here, the results are revisited on the basis of improved constitutive description and analysis of the work hardening rates.

3. Results and discussion

3.1. DRX flow behavior

The stress–strain (σ–ε) curves at various conditions for both steels are shown in Fig. 1. As can be seen, all three types of DRX flow curves can be identified: single peak, multiple transient steady state (MTSS), and cyclic behaviors.

At high strain rates and low temperatures, the shape of flow curves can be characterized as single peak behavior. In this type, more cycles of DRX initiate before the completion of the first one and the averaged flow stress of different grains will be in the form of a smooth peak. Moreover, the peak and steady state stresses decrease with an increase in the forming temperature or a decrease in strain rate. Conversely, at low strain rates and high temperatures, a multiple peak (cyclic) behavior can be noticed, in which the repetition of stress fluctuations is observed before the onset of steady state in the flow curves. This fact is attributed to the occurrence of several independent cycles of DRX. Furthermore, there are signs of another type of DRX flow curves, which can be considered as a transition state between single and cyclic behaviors. For instance, as can be seen in Fig. 2 for the deformation condition of 1050 °C–0.003 s^{-1}, several plateaus (horizontal stress lines) followed by a decrease in flow stress after each plateau can be detected beyond the peak stress of the flow curve. Each plateau represents a transient steady state period (similar to a peak point), and the decrease in flow stress after each plateau may be attributed to the progress of a new DRX cycle. This condition was also observed in a stainless steel alloy and subsequently was named as multiple transient steady state (MTSS) behavior [2,3]. This implies that the MTSS behavior might be a general flow behavior.

3.2. Work hardening rate analysis

The critical stresses for initiation of DRX (σ_C) were obtained from the inflection points in the work hardening rate ($\theta = d\sigma/d\varepsilon$) versus flow stress ($\sigma$) curves (before the peak stress) or from the minimums in the $-d\theta/d\sigma$ versus σ curves [16,17]. The former plots were used to determine other characteristic stresses. The critical strains for the onset of DRX (ε_c) were found directly from the inflection points of the ln θ–ε curves while other characteristic strains were determined from the θ–ε curves. More details are shown in Fig. 3. To obtain the values of θ, the following incremental equation was used:

$$\theta\big|_i = \frac{d\sigma}{d\varepsilon}\bigg|_i = \frac{\sigma|_{i+1} - \sigma|_{i-1}}{\varepsilon_{i+1} - \varepsilon_{i-1}} \tag{1}$$

Fig. 4 shows the relations among the various characteristic points of flow curves for both steels. Regression analysis of these curves (using an equation of the form of $y = ax$ based on the expected relations between the characteristic points) shows that $\sigma_C = 0.879\sigma_P$, $\varepsilon_C = 0.537\varepsilon_P$, and $\sigma_S = 0.875\sigma_P$ for the medium carbon steel and $\sigma_C = 0.846\sigma_P$, $\varepsilon_C = 0.531\varepsilon_P$, and $\sigma_S = 0.886\sigma_P$ for the low carbon steel. An interesting finding is the independency of the σ_C/σ_P and $\varepsilon_C/\varepsilon_P$ ratios on the carbon content. However, this does not mean that the level of σ_C, σ_P, ε_C or ε_P does not depend on the carbon content, as will be discussed later. Moreover, it can be seen that the normalized critical strain can be expressed as $\varepsilon_C/\varepsilon_P \approx 0.53$ for both steels. At the onset of steady state flow, as a result of the balance between work hardening and restoration processes, the flow stress reaches the value of $\sim 0.88\sigma_P$ for both steels. This implies that the restoration processes can effectively soften the alloy during hot working. The obtained value of normalized critical strain is also consistent with previous studies (mainly on steels) which have reported a value in the range of 0.3–0.9 [3]. The normalized critical strain of ~0.53 is lower than the one reported for medium carbon microalloyed steel (~0.62) [18], which reveals that carbon does not significantly affect this value but the microalloying elements are effective in retardation of recrystallization.

3.3. Constitutive modeling

One of the most-widely used parameters in hot deformation studies is the Zener–Hollomon one (Z), which is also known as the temperature-compensated strain rate. The basic constitutive equations in hot working are based on expressing Z as a function of flow stress as shown below [7,8]:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) = \begin{cases} A'\sigma^{n'} \\ A''\exp(\beta\sigma) \\ A[\sinh(\alpha\sigma)]^n \end{cases} \tag{2}$$

In this equation, Q is the hot deformation activation energy, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature, and finally A', A'', A, n', β, n, and α are the material's parameters. The power law is preferred for relatively low stresses. Conversely, the exponential law is suitable for high stresses. Finally, the hyperbolic sine law can be used for a wide range of Z parameters. The stress multiplier α is an adjustable constant which brings $\alpha\sigma$ into the correct range that gives linear and parallel lines in ln $\dot{\varepsilon}$ versus ln { sinh($\alpha\sigma$)} plots and it can be estimated by $\alpha \approx \beta/n'$.

By taking natural logarithm from both sides of the expressions of Eq. (2), the following expressions can be obtained:

$$\ln Z = \ln\dot{\varepsilon} + \frac{Q}{RT} = \begin{cases} \ln A' + n'\ln\sigma \\ \ln A'' + \beta\sigma \\ \ln A + n\ln[\sinh(\alpha\sigma)] \end{cases} \tag{3}$$

Since the deformation mechanism during hot working is usually based on the glide and climb of dislocations, the lattice self-diffusion activation energy can be employed as the deformation activation energy to determine Z [19]. As a result, the value of $Q_{SD} = 270$ kJ/mol [8,18] was considered for both steels in this work. Based on Eq. (3), the partial differentiation of the power and exponential laws leads to the following expressions at a given deformation temperature and for the particular case of the peak stress as follows:

$$n' = [\partial\ln\dot{\varepsilon}/\partial\ln\sigma_P]_T \tag{4}$$

$$\beta = [\partial\ln\dot{\varepsilon}/\partial\sigma_P]_T \tag{5}$$